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NASA CR-
151630

January 1978 SC577.51AR

INTERNAL FRICTION Q FACTOR MEASUREMENTS IN LUNAR ROCKS

ANNUAL REPORT NO. 4

For Period 01/01/77 thru 12/31/77

Contract No. NAS9-13846

General Order No. 577

Prepared for:

National Aeronautics and Space Administration
Lyndon B. Johnson Space Center
Science and Applications Directorate
Houston, Texas 77058

N78-17977
(NASA-CR-151630) INTERNAL FRICTION Q FACTOR MEASUREMENTS IN LUNAR ROCKS Annual Report, 1 Jan. - 31 Dec. 1977 (Rockwell International Corp., Thousand Oaks) 6 p HC A02/MF A01 CSCL 03B G3/91 Unclas 05340

FEB 1978

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) INTERNAL FRICTION Q FACTOR MEASUREMENTS IN LUNAR ROCKS - ANNUAL REPORT NO. 4		5. TYPE OF REPORT & PERIOD COVERED Annual Report 01/01/77 thru 12/31/77 6. PERFORMING ORG. REPORT NUMBER SC577.51AR
7. AUTHOR(s) B.R. Tittmann		8. CONTRACT OR GRANT NUMBER(s) NAS9-13846
9. PERFORMING ORGANIZATION NAME AND ADDRESS Science Center, Rockwell International 1049 Camino Dos Rios Thousand Oaks, CA 91360		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS National Aeronautics and Space Administration Lyndon B. Johnson Space Center Houston, Texas 77058		12. REPORT DATE January 1978 13. NUMBER OF PAGES 5
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

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17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Quality factor Q, confining pressure, basalt, volatiles, attenuation, seismic waves, terrestrial analog, absorbed H_2O, internal friction, damping, elastic modulus, absorption, vacuum, outgassing

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

In order to better interpret recently reported values for the variation of seismic Q as a function of depth below the lunar surface, we have developed apparatus and made laboratory measurements of Q as a function of hydrostatic pressure, temperature and frequency. Our measurements of the Q associated with shear deformations at pressures up to 2.5 kbar at room temperature have demonstrated that the large difference in Q between well outgassed and volatile-rich rocks persists to pressures corresponding to a depth of at least 50 km. Here we report new measurements of Q as a function of temperature, on the development

of techniques to measure the Q associated with extensional deformations under hydrostatic pressure, on the derivation of theoretical relations between our laboratory Q values and the attenuation coefficient of seismic waves, and on the development of a model for the mechanism of adsorption.

INTERNAL FRICTION AND MODULUS MEASUREMENTS IN LUNAR AND LUNAR ANALOG ROCKS

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In order to aid in the interpretation of the recently reported seismic Q versus depth profiles[1,2] we have begun laboratory Q measurements as a function of hydrostatic pressure, temperature, and frequency. We have already reported[3] Q_S (shear wave) measurements up to 2.5 kbar at room temperature and demonstrated that the dramatic differences in Q between thoroughly outgassed and volatile-rich rock persist to confining pressures corresponding to a depth of at least 50 km. Here we report on measurements of Q as a function of temperature, on the development of techniques to measure Q_p (longitudinal wave) under hydrostatic pressure, on the derivation of theoretical relations between laboratory Q and seismic attenuation, and on the development of a model for the absorption mechanism.

(1) Temperature Dependence

Q measurements were performed in the temperature range - 100 to 450° C on lunar rock 70215.85 and on analogs of lunar basalt at a frequency of about 50 Hz. The measurements were carried out at 2×10^{-7} Torr with our low frequency flexural apparatus[4] modified for the admission of dry N_2 cooled to -100° C into a Cu tube surrounding the furnace and sample. The system was calibrated with a sample of fused silica which gave a background (apparatus) Q well above the values measured for the rock samples. A conspicuous feature of the rock data is the systematic increase in Q as the temperature is lowered to -100° C. This feature has been observed by us also in the 10 kHz range and aside from the detailed structure of the curves is qualitatively repeatable from run to run, and sample to sample. The result suggests that the cool ($\sim$ -40° C) dry near-surface regions of the lunar crust should also give high Q values. Table I summarizes the results at high temperatures and shows that except for a moderate increase in Q at 100-200° C, the high Q values are observed to at least 450° C.

(2) Measurements of Q_p Under Hydrostatic Pressure

The measurement of Q for a bar vibrating in the extensional mode is straightforward under ambient conditions but becomes apparently meaningless at high confining pressures when the radiative losses into the pressure medium become excessive. (The Q of a metal rod decreases by a factor of 3 when subjected to a He pressure of only 0.8 kbar.) We have overcome this difficulty by rounding the end pieces of the vibrating bar to an aerodynamically low drag shape and have been able to obtain similarly high Q ($Q \doteq 1.0 \times 10^4$) on a polycrystalline Mo bar at 1 kbar as at ambient pressure. Since the rock samples are clad in a Cu sheath the measured modulus must be corrected for the cladding and we have derived the formulae to calculate the Young's modulus of the rock itself. Measurements carried out in the extensional mode for a well-outgassed analog of lunar basalt show roughly the same Q values as those obtained for the torsional mode over the hydrostatic pressure range studied (0-1.6 kbar).

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(3) Relationship between Laboratory Q and Seismic Q

In an effort to establish a quantitative relationship between the seismic data obtained for plane traveling waves and the laboratory data obtained in vibrating bars at resonance, we have derived the necessary theoretical expressions for both shear and longitudinal waves. Assumptions made in the derivation are that the strain amplitudes are small so that only linear processes are involved, that the internal friction is small ($Q > 10$) and that the microstructure and the processes associated with it have characteristic scales short compared with the wavelengths, so that the Lame' constants μ and λ may be expressed as complex functions of frequency. Under these assumptions and measurements of the density, the torsional and extensional modulus and the corresponding Q values, we are now able to calculate Q_p, Q_s, v_p, and v_s for seismic waves.

(4) Model for Absorption Mechanism

The results presented here and in previous reports have provided valuable clues to the mechanism by which an elastic wave is damped in a volatile-rich rock, and we summarize here the principal features of the absorption model which these clues suggest. Our observed increases in Q from $Q \approx 50$ in laboratory air to as high as $Q \approx 4800$[5] in vacuum after strong outgassing demonstrate that the removal of trace amounts of adsorbed volatiles play the dominant role in the absorption mechanism. The Q measurements under hydrostatic pressures to 2.5 kbar[3] show that the absorption mechanism caused by adsorbed volatiles is not inhibited by the partial closing of fractures under confining pressure, and probably involves active sites at grain boundaries throughout the rock. The experiments with a great variety of volatiles[6] show that adsorbed H_2O is by far the most effective volatile in reducing Q, most likely because of the well known strong bonding between H_2O and SiO_2 molecules. The results of ellipsometric experiments[3] demonstrate that the strong absorption of H_2O onto the rock surface does not lead to a uniformly covering layer of H_2O many tens or hundreds of monolayers thick. Rather the H_2O molecules must absorb preferentially onto active surface sites and diffuse into the interior of the rock. Depending on the specific nature of the fracture system of the rock and the influence of H_2O on the cracks and pores, the H_2O can reside as molecular water in sites favoring capillary condensation or as absorbed species on grain and crack boundaries. The systematic increase in Q with decreasing temperature (without a discontinuous jump at 0° C) represents the immobilization of any traces of H_2O still present after the long term outgassing treatment. These results prompt us to propose a model for the absorption mechanism which involves changes in the bonding, structure, and coverage of the molecular, physisorbed, and chemisorbed H_2O at the crack and grain boundaries. We present the details of the model and a theoretical approach to describe the processes involved.

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TABLE I

Temperature Dependence of Q at 56 Hz
for a Terrestrial Analog of Lunar Basalt

T (°C)	Q	Conditions
450	900	In vacuum
350	950	of 10^{-7} Torr
250	900	after strong
150	700	outgassing
50	1000	

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